Resolving the Intrinsic C IV Absorption in the Seyfert 1 Galaxy NGC 3516[1]

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ABSTRACT

We observed the Seyfert 1 galaxy NGC 3516 with the Goddard High Resolution Spectrograph on the Hubble Space Telescope, and obtained UV spectra at a resolution of $\lambda/\Delta\lambda \approx 20{,}000$ in the redshifted C IV $\lambda1549$ region. The intrinsic C IV absorption in the core of the broad emission line is resolved for the first time into four distinct kinematic components, which are all blue-shifted relative to the systemic radial velocity of the host galaxy. Two components are narrow ($\sim$20 and $\sim$30 km s^{-1} FWHM) and at small radial velocities (-90 and -30 km s^{-1} respectively), and could arise from the interstellar medium or halo of the host galaxy. The two broad components are centered at radial velocities of -380 and -150 km s^{-1}, have widths of 130 and 210 km s^{-1} FWHM respectively, and most likely arise in outflowing gas near the active nucleus. At the times of observation, 1995 April 24 and 1995 October 22, there was no evidence for the variable absorption component at a higher outflow velocity that disappeared some time after 1989 October (Koratkar et al. 1996).

The cores of the broad C IV absorption components are very close to zero intensity, indicating that the absorption regions are extended enough to completely occult the broad C IV emitting region (which is $\sim$9 light days in extent). The total column density of the C IV absorption is substantially larger than that measured by Kriss et al. (1996a) from contemporaneous HUT spectra, but we agree with their conclusion that the UV absorption is too strong to arise primarily from the X-ray warm absorber region. The GHRS observations separated by six months reveal no appreciable changes in the equivalent widths or radial velocities of any of the absorption components, although a change in the column density of either broad component at a level $\leq$ 25% cannot be ruled out, because the lines are highly saturated. At present, we know of two Seyfert

galaxies, NGC 3516 and NGC 4151 (Weymann et al. 1997), with complex multiple absorption zones that can remain stable in column density and velocity field over time scales of months to years.

Subject headings: galaxies: individual (NGC 3516) – galaxies: Seyfert

1. Introduction

NGC 3516 is one of the few Seyfert 1 galaxies with intrinsic absorption lines that were strong enough to be detected by the International Ultraviolet Explorer (IUE). The UV absorption is characterized by high-ionization resonance lines (C IV $\lambda\lambda$1548.2, 1550.8; N V λ1238.8, 1242.8; and Si IV $\lambda\lambda$ 1393.8, 1402.8) that are blueshifted with respect to the host galaxy. The absorption lines were originally studied by Ulrich and Boisson (1983) and were recognized as being intrinsic to the nucleus from their large widths (extending from zero to -3000 km s^{-1} relative to the redshift of the host galaxy), equivalent widths (up to $\sim$4 Å for C IV), and variability (on time scales of months). Subsequent IUE monitoring found evidence for absorption-line variations on time scales as small as weeks (Voit et al. 1987; Walter et al. 1990; Kolman et al. 1993).

Walter et al. (1990) characterized the C IV absorption in NGC 3516 as a blend of a narrow stable component near the center of the broad C IV emission profile, and a variable and broad blueshifted component. Koratkar et al. (1996) found that the variable component was present in IUE spectra since the first IUE observation in 1978, but disappeared between 1989 October and 1993 February, when there were no IUE observations. More recent spectra obtained with the Hopkins Ultraviolet Telescope (HUT) show that the variable blueshifted component was not present in 1995 March (Kriss et al. 1996a).

NGC 3516 also exhibits strong and variable X-ray absorption in the form of a "warm absorber" (Kolman et al. 1993; Nandra & Pounds 1994; Kriss et al. 1996b; Mathur et al. 1997). The warm absorber is highly ionized gas characterized by high ionization parameters (U $\approx$ 1 – 10) and correspondingly high temperatures (T $\approx 10^5$K), and is most easily identified from the presence of O VII and O VIII absorption edges (see Reynolds & Fabian 1995, and references therein). UV absorbers and X-ray warm absorbers are thought to be related, because they both occur in the same objects (Crenshaw 1997), but the

exact nature of the relationship is unclear. In some AGN, they could both arise from gas characterized by a single ionization parameter (Mathur 1994; Mathur et al. 1996). However multi-component models that span a wide range in ionization parameter are needed to explain the column densities of the UV and X-ray absorption features in NGC 3516 (Kriss et al. 1996a) and NGC 4151 (Kriss et al. 1995; Weymann et al. 1997).

Since none of the previous UV observations of NGC 3516 have resolved the velocity structure in the C IV doublet, we decided to observe this region at a spectral resolution at least ten times that of any prior observation. The observations are part of an ongoing study to understand the nature of the intrinsic absorption in low-redshift Seyfert galaxies; results on the variable C IV absorption in NGC 3783 have already been published (Maran et al. 1996). For this investigation, we obtained observations of NGC 3516 with the Goddard High Resolution Spectrograph (GHRS) on two occasions in 1995 separated by six months.

2. Observations and Direct Measurements

We observed NGC 3516 with the GHRS side 2 detector and G160M grating on 1995 April 24 and 1995 October 22. (The GHRS was removed from the HST during the Second Servicing Mission in 1997 February.) The observations were made in conjunction with the corrective optics package COSTAR through the Large Science Aperture ($1''.74$ x $1''.74$), providing a spectral resolution of $\lambda/\Delta\lambda \approx$ 20,000 (λ is the observed wavelength and $\Delta\lambda$ is the FWHM of an instrumental profile). For each observation, we used two grating wheel settings to cover the wavelength regions 1528.5 – 1564.6 Å and 1561.3 – 1597.3 Å. Exposure times on the target were 121.6 min per setting for the 1995 April spectra and 101.4 min per setting for the 1995 October spectra.

We reduced the spectra using the IDL procedures written for the GHRS Instrument

Definition Team (Blackwell et al. 1993). For each readout, an average background across the diode array was determined and subtracted from the gross spectrum, since the background level (due primarily to Cerenkov radiation) is constant to within a few percent as a function of diode, but generally variable by a factor of two as the geomagnetic latitude of HST changes over time (Ebbets 1992). In the regions of overlap, the average fluxes from the two wavelength settings agree to within 4%, so no scaling was done between them. The signal-to-noise ratio (per half resolution element) ranges from 8 to 15 for the combined 1995 April spectrum and 6 to 13 (wings to peak) for the combined 1995 October spectrum.

Figure 1 shows the two GHRS spectra (smoothed by a five-point boxcar for display purposes), which encompass most of the broad C IV emission profile. All of the significant absorption features in Figure 1 are due to the resolved C IV $\lambda\lambda$1548.2, 1550.8 doublet at different radial velocities, including the strong Galactic lines in the blue wing of the emission profile. The intrinsic C IV absorption is located in the core of the emission profile, and is clearly separated into a number of distinct components. The variable highly blue-shifted component that disappeared after 1989 is still not present in these spectra.

In order to determine the strength of the absorption components, the shape of the underlying emission must be characterized. The 1995 April spectrum is at a higher flux level, primarily as a result of a continuum level that is $\sim$3 x 10^{-14} erg s^{-1} cm^{-2} Å^{-1} higher (as estimated from the far red wing). The broad emission profiles are asymmetric, with more emission in the blue wing than the red wing. In addition, the 1995 April profile has relatively more emission just blueward of the core than the 1995 October profile. To estimate the underlying broad emission in the core of each profile, we fit a cubic spline to regions on either side of the core; the fits are shown as dotted lines in Figure 1. Note that the flux may be underestimated if there is a significant narrow-line contribution to the C IV emission.

We normalized the absorption lines in the core of the emission profile by dividing by the cubic spline fits to the emission core (plus underlying continuum); the resulting (unsmoothed) absorption profiles are shown in Figure 2. The intrinsic C IV absorption can be separated into four distinct kinematic components. The radial velocities of the kinematic components are such that there is essentially no overlap in wavelength of the C IV doublet lines. The components that we have labeled 1 and 2 are broad and very deep, approaching zero intensity. Components 3 and 4 are narrow, but are clearly seen in each member of the doublet on both occasions. The absorption profiles obtained on the two dates are visually quite similar.

We made direct measurements of the centroid, equivalent width (EW), and full-width at half-maximum (FWHM) of each absorption component – these values are listed in Table 1. Each line is identified as a member of the C IV doublet, and its heliocentric radial velocity (cz) from the line's centroid is given. There is no evidence that components 3 and 4 have broad wings, so we determined a baseline for measurements of these components from adjacent regions in the red wing of component 2. Errors in EW are the sums in quadrature of the uncertainties (one standard deviation) from photon noise and the estimated errors from different reasonable placements of the fit to the core of the emission line. Errors for the other measurements were estimated in the same way, and yield values around ±10 km s^{-1} for both FWHM and radial velocity. Given the errors, there is no evidence for changes in position, width, or equivalent width of any of the components over a six-month interval.

3. Optical Depths and Covering Factors

Here we present the details of determining the column densities of the intrinsic absorption components from their optical depths and covering factors. The instrumental profile has a FWHM of 15 km s^{-1}, so each of the C IV absorption components in Table

1 is resolved. Hence we can determine the column density of each intrinsic component by integrating its optical depth as a function of radial velocity across the profile (Savage & Sembach 1991). The radial velocities are determined with respect to the systemic radial velocity of the host galaxy, which we take to be cz = 2634 km s^{-1} from long-slit spectra of the narrow Hα emission (Keel 1996). This value is in good agreement with cz = 2649 km s^{-1} from the stellar absorption lines (Vrtilek & Carleton 1985). The optical depth is just

$$\tau(v_r) \;=\; ln\;[F_0(v_r)/F(v_r)], \tag{1}$$

where $F_0(v_r)/F(v_r)$ is the ratio of continuum to observed flux, or the inverse of the normalized flux in Figure 2. To avoid the problem of occasional negative values for the normalized fluxes in Figure 2 due to the noise level, we binned the fluxes in the cores of components 1 and 2 to 0.14 Å intervals (∼2 resolution elements), and kept the original bin widths (0.0175 Å) for the remaining portions of the profiles.

Figure 3 shows plots of the observed optical depths as a function of radial velocity. Each of the four kinematic components can be easily distinguished in these plots. It is obvious that the broad components are *not* optically thin, with $\tau(v_r) \approx 4 - 6$ in the cores, so assuming that the lines are unsaturated would severely underestimate the column densities. Errors in the optical depths were determined from propagation of the original errors (section 2), and can be quite large in the cores despite the large bins. Given the errors, the apparent differences in structure in the cores of the lines are not significant.

The ratio of C IV λ1548.2 to C IV λ1550.8 optical depth should be 2, since the optical depths are proportional to fλ (where f is the oscillator strength). However, Figure 3 shows that the ratios are ∼1.6 and ∼1.2 in the cores of components 1 and 2 respectively. This can be explained by an additional unabsorbed contribution to the flux, which alters the observed optical depth ratio. The two most likely explanations for an unabsorbed contribution are: 1) the background emission is partially covered, or 2) there is an instrumental contribution

(i.e., grating scattered light). In either case, the unabsorbed flux can be determined by forcing the ratio of optical depths for the C IV doublet to be 2, and using the formulae given by Hamann et al. (1997) to calculate the covering factors in the line of sight (C_f) and corrected optical depths as a function of radial velocity.

We calculated the covering factor for each component and, given the signal-to-noise, found no evidence for variation of covering factor with radial velocity. We therefore determined average covering factors (and their dispersions) for each component; the broad component values are listed in Table 2 and the narrow component values are discussed below. It is obvious from inspection of Figure 2 that the covering factors for the broad components are close to one, but Table 2 shows that they are not identical to one. Since the broad components approach zero intensity in their cores, even a small contribution from unabsorbed light can alter their observed optical depths significantly. To demonstrate this point, we used the average covering factor for each broad component to calculate the corrected optical depths as a function of radial velocity. Then we integrated both observed and corrected optical depths over radial velocity for each component, and computed the ratio:

$$R_\tau = \int \tau_{corrected}(v_r)dv_r / \int \tau_{observed}(v_r)dv_r. \tag{2}$$

This is the factor by which the column density increases when a correction is made for a partial covering factor. From Table 2, one can see that this correction can be quite significant for these data, particularly for the λ1548.2 component. We conclude that correction for unabsorbed light is important for reconciling the doublet optical depths and determining the correct column densities of the broad absorption components in NGC 3516.

The narrow components, which we separated from broad component 2, are noisy and yield only approximate values: $C_f \approx 1.0 \pm 0.3$. Since the narrow components are shallow, R_τ is roughly proportional to $1/C_f$. Thus, we adopt a value of $C_f = 1$ for the narrow

components, with the understanding that the error in optical depth due to uncertain covering factor is ∼30%.

Since the covering factors for the components are all suspiciously close to one, and scattered light is a basic property of gratings, we conclude that the excess light is due to instrumental scattering, which is at the level of 2.5 ± 1.5% (the average value of 1 − C_f). This value is in agreement with the value of ∼1.8% determined by Ebbets (1992), which was calculated from GHRS G160M spectra of interstellar absorption lines at 1670 Å. Thus, we believe that the true covering factor for each of the intrinsic C IV components is essentially one (with much higher certainty for the broad components), and we have used the "effective" covering factors in Table 2 to correct the optical depths of the broad components for grating scattered light.

We obtained the C IV column densities by integrating the corrected optical depths across each component (Savage & Sembach 1991):

$$N(CIV) = \frac{m_e c}{\pi e^2 f \lambda} \int \tau(v_r) dv_r, \tag{3}$$

and we obtained the errors in column densities from the combination of errors in observed optical depths and covering factors. Our final values of the radial velocities (relative to the systemic velocity) and widths (FWHM) are averages based on the doublet from each kinematic component.

4. Properties of the Intrinsic Absorption

For the first time, we can determine properties such as covering factor, column density, radial velocity, and variability of the individual kinematic components of the C IV absorption in NGC 3516. We have already shown that the covering factor for each absorption component is essentially one and we know from IUE monitoring of the continuum

and emission lines in NGC 3516 that the size (i.e. radius) of the C IV emitting region is $\sim$4.5 light days (Koratkar et al. 1996). Thus, the extent of the individual absorption regions in the plane of the sky must be $\geq$ 9 light days. In addition, the UV absorbing regions must lie completely outside of the broad C IV emitting region, at distances $\geq$4.5 light days from the continuum source.

Table 3 provides a summary of the other important properties of the C IV absorption in NGC 3516. Components 3 and 4 have relatively small column densities, small radial velocities, and narrow widths. These components could easily arise from the interstellar medium or halo of the host galaxy; their properties are less extreme than those of the C IV absorption lines in our Galaxy (Table 1). Components 1 and 2 are much stronger and broader, and at higher radial velocities relative to the nucleus. These properties are all suggestive of outflowing gas close to the nucleus.

Comparing the two GHRS observations separated by six months, there is no evidence in Table 3 for variations in any of the properties of any component (given our estimates of the errors). The radial velocity coverage of the absorption components is also the same for the two observations (see Figure 2), which indicates a very stable velocity field over this six-month period. There is also no evidence for changes in the column density of any component, although the errors indicate that a variation of $\sim$25% or less cannot be ruled out for any component.

Kriss et al. (1996a) obtained HUT spectra of NGC 3516 on 1995 March 11 and 13 (as well as near-simultaneous X-ray spectra with ASCA). The C IV doublet is resolved in the HUT spectra ($\lambda/\Delta\lambda \approx 500$), but the individual kinematic components are not. These authors determine a total C IV column density of 4.7 x 10^{14} cm^{-2}, whereas if we sum our C IV column densities over all of the components in the GHRS spectra, we obtain values that are $\sim$5 times higher. Since the HUT observations were obtained only one month

prior to our first observation, and there is no evidence for variations six months later, it is unlikely that our higher values are due to a real variation in the column density. It is more likely that they are due to our higher spectral resolution, which allows us to determine the shape of the underlying emission profile more accurately, and more importantly, detect the large optical depths in the broad components. (To support this claim, we note that the column densities in Table 3 are ∼3 times higher than those that would be determined from the GHRS spectra assuming unsaturated lines.) In general, the GHRS data show the importance of high spectral resolution for estimating the underlying emission, resolving the velocity structure, and directly determining the column densities of the intrinsic absorption components from their optical depths.

It is tempting to associate the UV absorbers with the X-ray warm absorber in NGC 3516. For some active galaxies, the UV and X-ray column densities have been successfully matched with photoionization models characterized by a single photoionization parameter, assuming a "typical" XUV spectrum and standard cosmic abundances (Mathur et al. 1994; Mathur, Wilkes, & Elvis 1995). However, the *total* column densities of the UV lines in NGC 3516 and NGC 4151 are much too high to arise entirely in the highly-ionized warm absorber gas, based on the analyses of Kriss et al. (1995, 1996a). With the ability to resolve the C IV absorption, we can ask if any of the individual kinematic components are likely to arise from the warm absorber. Components 3 and 4 have C IV column densities that are a factor of ten lower than the value of ∼5 x 10^{14} predicted by the warm absorber model of Kriss et al. (1996a), and as we pointed out earlier, they can be explained as absorption from the host galaxy. Components 1 and 2 have a combined C IV column density that is ∼ 5 times higher than their predicted value. Component 1 alone has a column density that is close to their predicted value, but there is no other evidence that it arises from the warm absorber. We also note the X-ray warm absorber appears to have varied in the year prior to these observations, long after the variable UV component had vanished. Comparsion of two

ASCA observations on 1994 April 2 (George et al. 1997) and 1995 March 11 – 12 (Kriss et al. 1996b) indicate that the optical depths of the O VII and O VIII edges were higher by a factor of two on the later date (George 1997). Thus, there is no clear connection between the UV and X-ray absorbers in this Seyfert.

5. Conclusions

The intrinsic absorption in NGC 3516 most closely resembles that in the Seyfert 1 galaxy NGC 4151, in that its UV absorption lines are characterized by very high column densities and a number of kinematic components, although the absorption in NGC 3516 does not extend to very low ionization lines such as Mg II (Koratkar et al. 1996). Weymann et al. (1997) monitored the intrinsic C IV absorption in NGC 4151 with the GHRS, and were able to place important constraints on the radial acceleration of the gas. They find at least 8 distinct components at radial velocities from 0 to $\sim$1600 km s $^{-1}$, spanning a range of widths and depths. The absorption components in NGC 4151 show little or no variation in equivalent width or radial velocity over a four-year period, like the observed components in NGC 3516 over a six-month period. Other Seyfert galaxies with known intrinsic absorption have lower C IV column densities, and those that have been monitored show evidence for equivalent width variations (Maran et al. 1996; Crenshaw 1997). At earlier epochs, NGC 3516 itself showed this behavior in the variable blueshifted component (Koratkar et al. 1996).

Intrinsic UV absorbers in Seyfert galaxies share a number of common properties, including outflow relative to the host galaxy, high ionization (C IV, N V), and broad profiles (100 km s^{-1} or more) that separate into more than one component at high resolution (Crenshaw 1997). However, there is also a wide range in some properties, including column density, variability, and extension to low ionization. Some properties, such as

covering factors and the fraction of active galaxies with intrinsic absorption, are not well known. High-resolution UV spectra of a number of absorption lines spanning a wide range in ionization level, along with concurrent X-ray spectra, are needed to determine the relationship between the multiple ionization and kinematic absorption components in NGC 3516, as well as those in other Seyfert galaxies.

Table 1. C IV absorption components in NGC 3516

λ_{obs} (Å)	EW (Å)	FWHM (km s^{-1})	Identification km s^{-1})	cz[a] (km s^{-1})	Component
			1995 April 24		
1547.85	0.29±0.04	75	C IV λ1548.2	−68	Gal.
1550.49	0.19±0.03	85	C IV λ1550.8	−54	Gal.
1559.87	0.75±0.04	138	C IV λ1548.2	2259	1
1561.04	1.11±0.04	220	C IV λ1548.2	2486	2
1561.34	0.04±0.02	17	C IV λ1548.2	2544	3
1561.63	0.08±0.02	29	C IV λ1548.2	2600	4
1562.44	0.59±0.02	121	C IV λ1550.8	2255	1
1563.63	0.99±0.02	207	C IV λ1550.8	2485	2
1563.96	0.04±0.02	17	C IV λ1550.8	2549	3
1564.23	0.07±0.02	25	C IV λ1550.8	2601	4
			1995 October 22		
1547.94	0.26±0.06	62	C IV λ1548.2	−51	Gal.
1550.52	0.16±0.05	81	C IV λ1550.8	−49	Gal.
1559.87	0.68±0.03	127	C IV λ1548.2	2259	1
1561.06	1.16±0.05	207	C IV λ1548.2	2490	2
1561.35	0.06±0.04	23	C IV λ1548.2	2546	3
1561.65	0.09±0.03	34	C IV λ1548.2	2604	4
1562.44	0.56±0.03	119	C IV λ1550.8	2255	1
1563.62	1.03±0.04	190	C IV λ1550.8	2483	2
1563.95	0.03±0.02	23	C IV λ1550.8	2547	3
1564.26	0.06±0.03	36	C IV λ1550.8	2607	4

[a]Adopted recession velocity for the host galaxy is 2634 km s^{-1} (Keel 1996).

Table 2. Covering factors for the broad components

Component	C_f	$R_\tau(\lambda1548.2)$	$R_\tau(\lambda1550.8)$
1995 April 24			
1	0.993 (±0.007)	1.27	1.04
2	0.984 (±0.009)	1.81	1.12
1995 October 22			
1	0.985 (±0.015)	1.29	1.05
2	0.951 (±0.016)	2.40	1.40

Table 3. Properties of the intrinsic C IV absorption

Component	N (C IV) (10^{-14}cm^{-2})	v$_r$ (km s^{-1})	FWHM km s^{-1})
	1995 April 24		
1	$8.4^{+0.5}_{-0.4}$	−377	130
2	$15.3^{+1.6}_{-1.0}$	−148	214
3	$0.4^{+0.1}_{-0.1}$	−88	17
4	$0.5^{+0.1}_{-0.1}$	−34	27
	1995 October 22		
1	$6.6^{+0.5}_{-0.4}$	−377	123
2	$15.4^{+4.2}_{-2.3}$	−148	198
3	$0.4^{+0.1}_{-0.1}$	−88	23
4	$0.5^{+0.1}_{-0.1}$	−29	35

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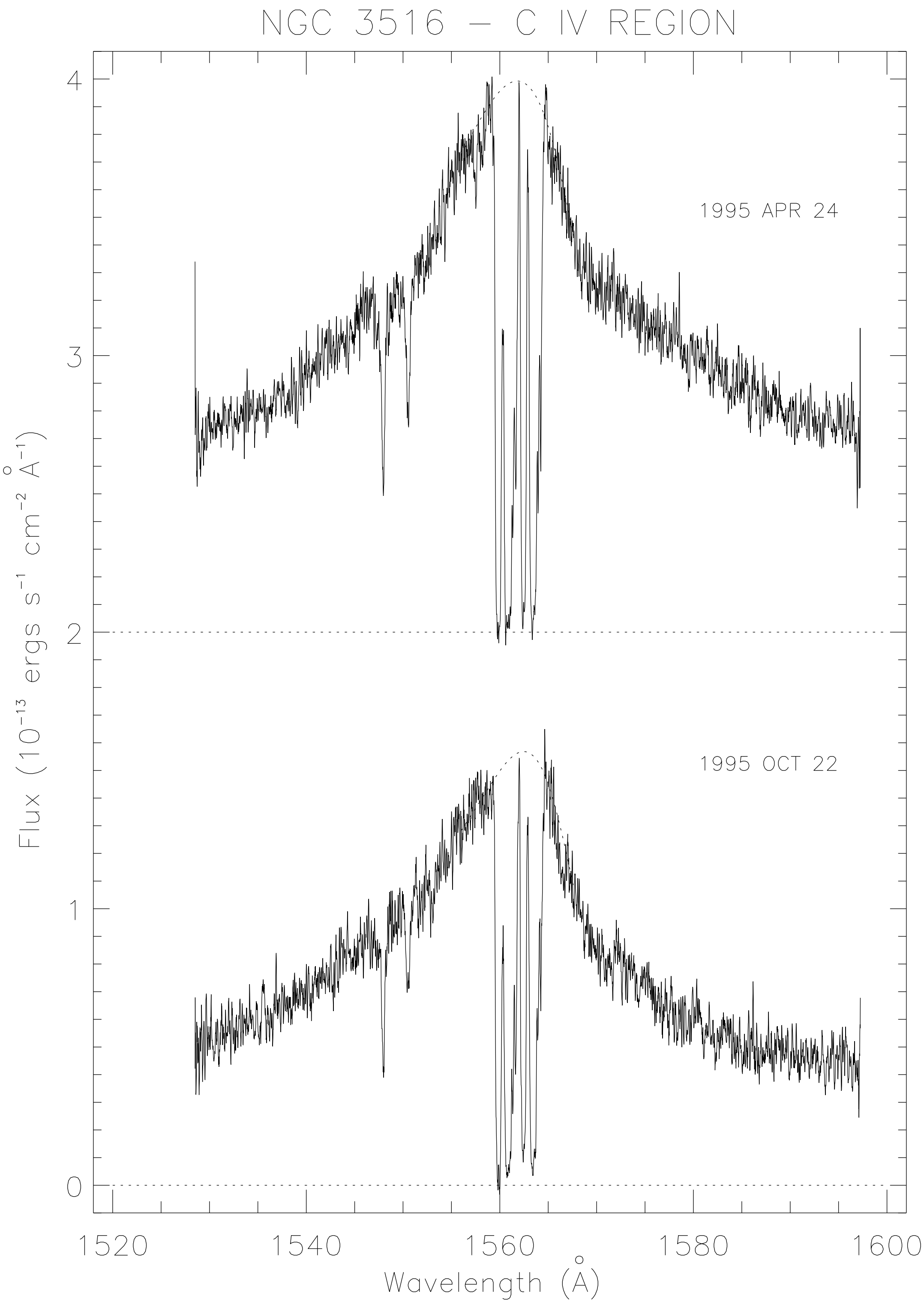
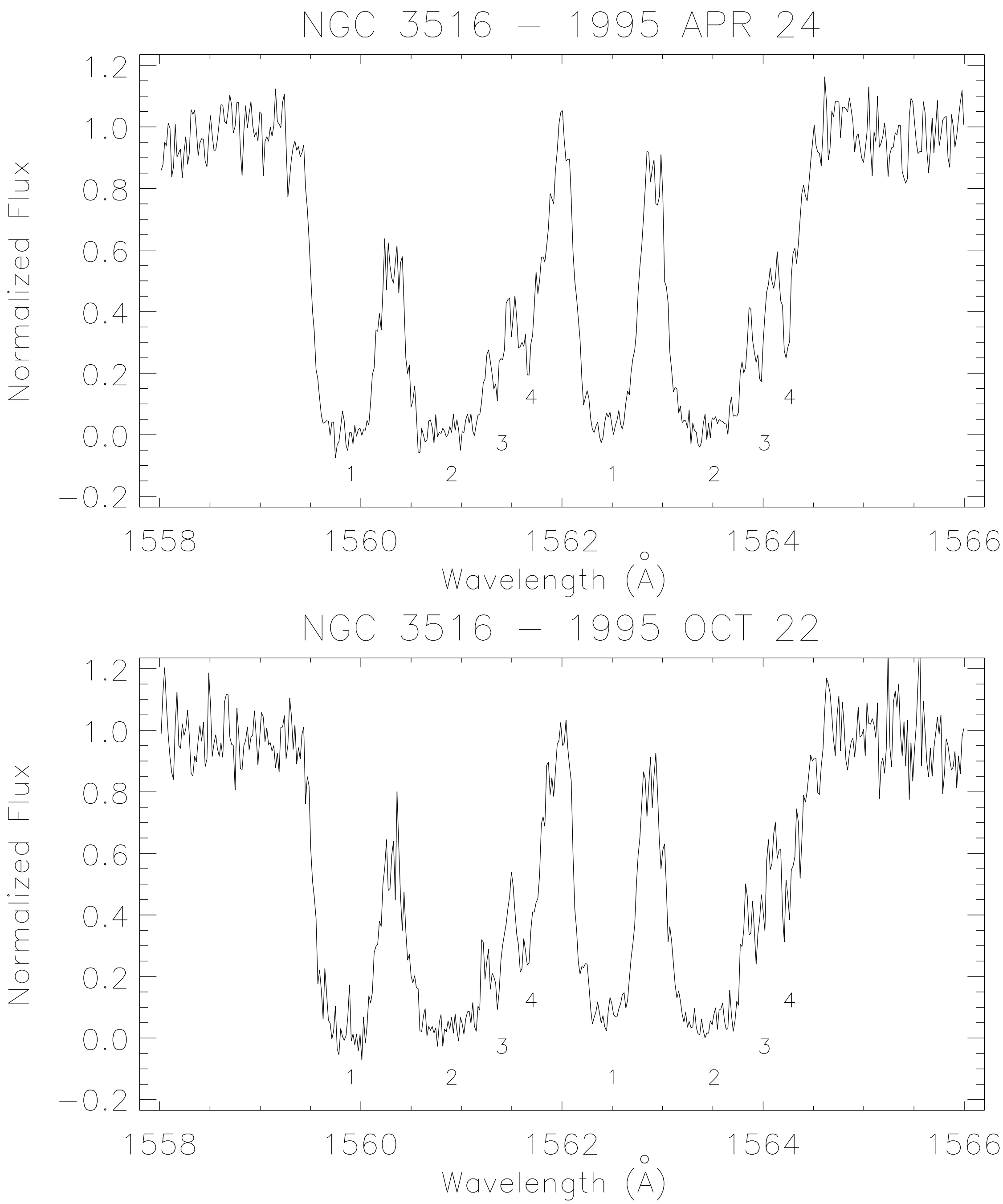
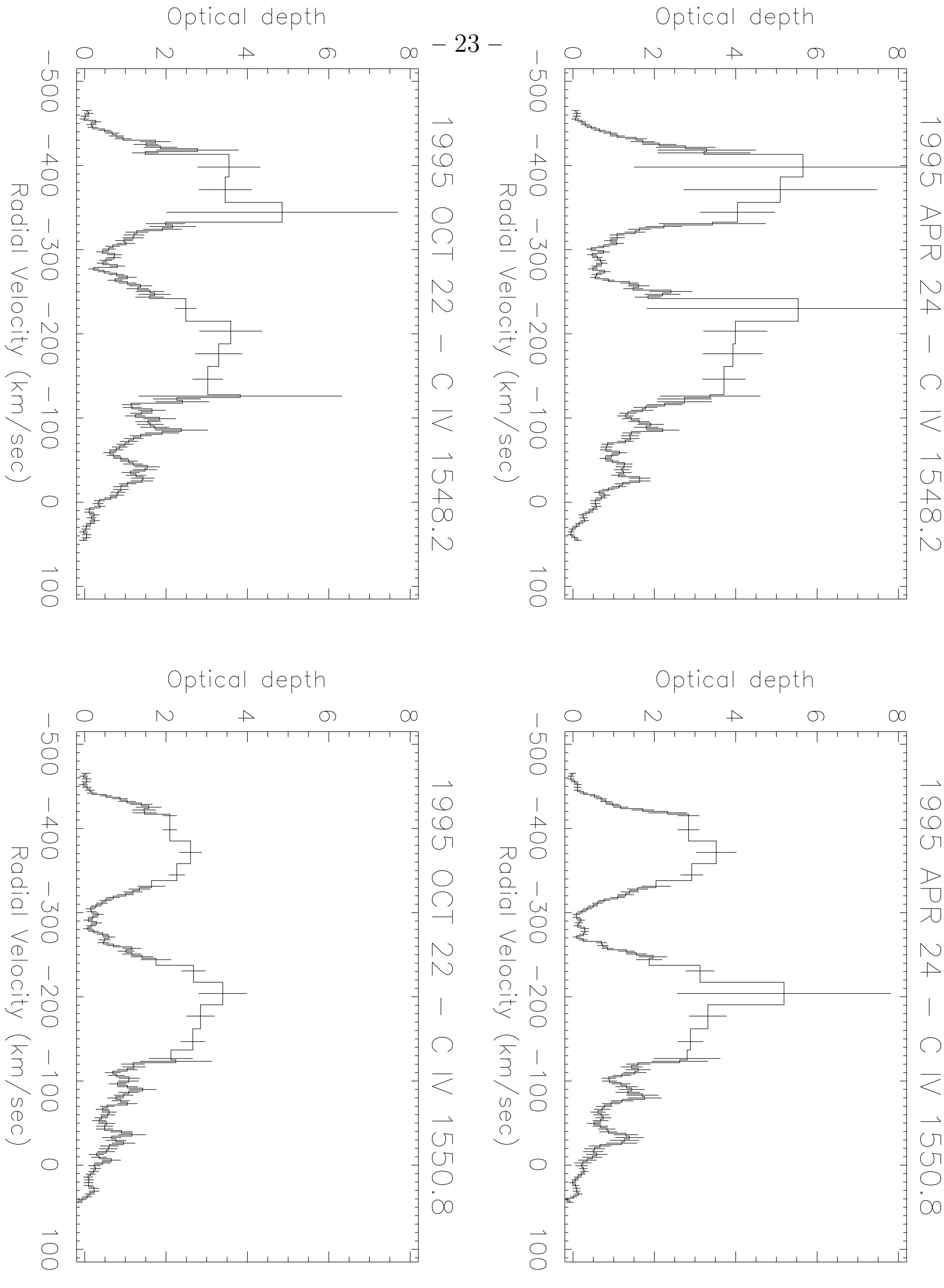
Fig. 1.— GHRS spectra of NGC 3516 in the C IV region, obtained on two separate occasions. The upper spectrum is offset by 2.0 x 10^{-13} erg s^{-1} cm^{-2} $Å^{-1}$. Galactic and intrinsic C IV absorption are evident in the blue wing and core of the emission profile respectively. A cubic spline fit to the core of the emission line is shown as a dotted line.

Fig. 2.— Normalized (unsmoothed) profiles of the intrinsic C IV absorption, obtained by dividing the observed spectrum by the fit to the emission core. Four distinct kinematic components of the C IV $\lambda\lambda$1548.2, 1550.8 absorption doublet are identified.

Fig. 3.— *Observed* optical depths of the intrinsic C IV absorption as a function of radial velocity (relative to the systemic radial velocity of the host galaxy.)


NGC 3516 – C IV REGION
1995 APR 24
1995 OCT 22
Flux (10^{-13} ergs s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
0
1
2
3
4
1520
1540
1560
1580
1600


NGC 3516 – 1995 APR 24
Normalized Flux
Wavelength (Å)
NGC 3516 – 1995 OCT 22
Normalized Flux
Wavelength (Å)
1
2
3
4
1
2
3
4



1995 APR 24 – C IV 1548.2
1995 APR 24 – C IV 1550.8
1995 OCT 22 – C IV 1548.2
1995 OCT 22 – C IV 1550.8
Optical depth
Radial Velocity (km/sec)